

### A search for an excited muon decaying to a muon and two jets in pp collisions at $s = 8$ TeV with the ATLAS detector

ATLAS Collaboration; Newman, Paul

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## A search for an excited muon decaying to a muon and two jets in $pp$ collisions at $\sqrt{s} = 8 \text{ TeV}$ with the ATLAS detector

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## PAPER

A search for an excited muon decaying to a muon and two jets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector

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## The ATLAS Collaboration

E-mail: [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch)

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## Abstract

A new search signature for excited leptons is explored. Excited muons are sought in the channel  $pp \rightarrow \mu\mu^* \rightarrow \mu\mu \text{ jet jet}$ , assuming both the production and decay occur via a contact interaction. The analysis is based on  $20.3 \text{ fb}^{-1}$  of  $pp$  collision data at a centre-of-mass energy of  $\sqrt{s} = 8$  TeV taken with the ATLAS detector at the large hadron collider. No evidence of excited muons is found, and limits are set at the 95% confidence level on the cross section times branching ratio as a function of the excited-muon mass  $m_{\mu^*}$ . For  $m_{\mu^*}$  between 1.3 and 3.0 TeV, the upper limit on  $\sigma B(\mu^* \rightarrow \mu q \bar{q})$  is between 0.6 and 1 fb. Limits on  $\sigma B$  are converted to lower bounds on the compositeness scale  $\Lambda$ . In the limiting case  $\Lambda = m_{\mu^*}$ , excited muons with a mass below 2.8 TeV are excluded. With the same model assumptions, these limits at larger  $\mu^*$  masses improve upon previous limits from traditional searches based on the gauge-mediated decay  $\mu^* \rightarrow \mu\gamma$ .

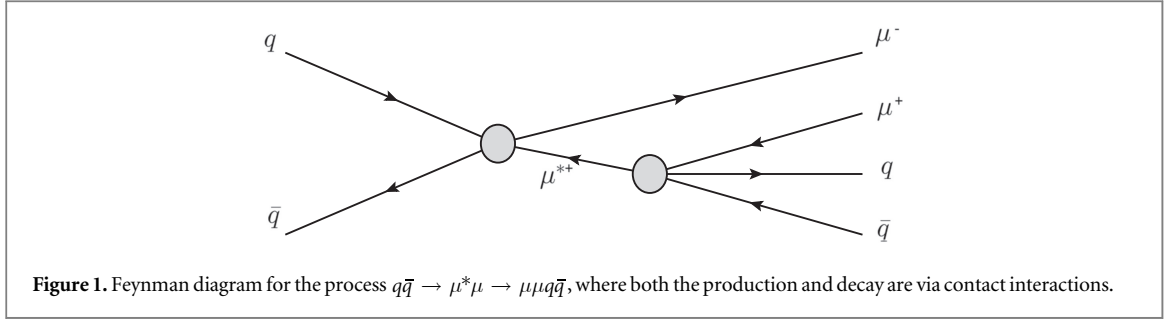
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## 1. Introduction

The standard model (SM) of particle physics successfully describes a wide range of phenomena but does not explain the generational structure and mass hierarchy of quarks and leptons. Composite models of fermions [1–7] aim to reduce the number of matter constituents by postulating that SM fermions are bound states of more fundamental particles. A direct consequence of substructure would be the existence of excited fermion states.

This paper reports on a search for an excited muon  $\mu^*$  using  $20.3 \text{ fb}^{-1}$  of  $pp$  collision data at a centre-of-mass energy of  $\sqrt{s} = 8$  TeV recorded in 2012 with the ATLAS detector at the large hadron collider (LHC). The search is based on a benchmark model [7] that describes excited-fermion interactions with an effective Lagrangian



containing four-fermion contact interactions and gauge-mediated interactions. A contact interaction decay signature not previously employed in excited leptons searches,  $\mu^* \rightarrow \mu j j$  ( $j$  represents a jet), is used.

In this paper, as in [7], the model is assumed to be valid for  $\mu^*$  masses up to the compositeness scale. The contact interaction terms are described by the Lagrangian

$$\mathcal{L}_{\text{contact}} = \frac{g_*^2}{2\Lambda^2} j_\mu^\mu j_\mu, \quad \text{with } j_\mu = \eta \bar{f}_L \gamma_\mu f_L + \eta' \bar{f}_L^* \gamma_\mu f_L^* + \eta'' \bar{f}_L^* \gamma_\mu f_L + \text{h.c.},$$

where  $\Lambda$  is the compositeness scale;  $j_\mu$  is the fermion current for ground states ( $f$ ) and excited states ( $f^*$ );  $g^*$  and the  $\eta$ 's are constants; 'h.c.' stands for Hermitian conjugate; and only left-handed fermion interactions are assumed. As is done in [7],  $g_*^2$  is set to  $4\pi$ , and  $\eta$ ,  $\eta'$ , and  $\eta''$  are taken to be one for all fermions. To calculate branching ratios, the compositeness scale  $\Lambda$  is assumed to be the same for gauge-mediated interactions, and the parameters  $f$  and  $f'$  in [7] are taken to be one.

The search described here focuses on the predominant single- $\mu^*$  production via the contact interaction ( $q\bar{q} \rightarrow \mu^*\mu$ ) followed by the decay of the excited muon via the contact interaction to  $\mu q\bar{q}$ , leading to a final state with two muons and two jets (figure 1). Top quarks from excited muons with masses accessible in the 8 TeV LHC data would not have sufficient energy to form narrow jets and are excluded from the analysis in this paper. Previous searches at LEP [8–11], the Tevatron [12–15], and the LHC [16–20] looked for the gauge-mediated decay  $\mu^* \rightarrow \mu\gamma$ . The analysis reported in [20] also includes the gauge-mediated decay  $\mu^* \rightarrow \mu Z$  followed by  $Z \rightarrow \ell\ell$  or  $q\bar{q}$ . In the model of [7], this decay is dominant at low  $\mu^*$  mass, but for  $m_{\mu^*} \gtrsim 0.25\Lambda$ , the  $\mu q\bar{q}$  decay mode is expected to have the largest branching ratio, rising to 65% for  $m_{\mu^*} = \Lambda$ . The search reported here complements the search in the  $\mu\gamma$  channel and increases the sensitivity of the search for excited muons at higher masses. The ATLAS Collaboration recently published [21] another new search signature for excited muons decaying via a contact interaction to  $\mu\ell\ell$ , where  $\ell$  is an electron or a muon.

## 2. ATLAS detector

The ATLAS experiment [22] uses a multi-purpose particle detector with a forward–backward symmetric cylindrical geometry and a near  $4\pi$  coverage in solid angle<sup>271</sup>. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range  $|\eta| < 2.5$ . It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A hadronic steel/scintillator-tile calorimeter covers the central pseudorapidity range ( $|\eta| < 1.7$ ). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to  $|\eta| = 4.9$ . The muon spectrometer surrounding the calorimeters covers the pseudorapidity range  $|\eta| < 2.7$  and is based on three large air-core toroid superconducting magnets with eight coils each. Their bending power is in the range from 2.0 to 7.5 Tm. The muon spectrometer consists of three stations of precision tracking chambers and fast detectors for triggering. The majority of the precision tracking chambers are composed of drift tubes, while cathode-strip chambers provide coverage in the inner stations of the forward region for  $2.0 < |\eta| < 2.7$ . A three-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to at most 75 kHz. This is followed by two software-based trigger levels that together reduce the accepted event rate to 400 Hz on average, depending on the data-taking conditions during 2012.

<sup>271</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upwards. Cylindrical coordinates ( $r$ ,  $\phi$ ) are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . Angular distance is measured in terms of  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .

**Table 1.** Summary of the background and signal MC sample generation used in this search. The columns give the process generated, the generator program, the parton shower program, and the PDF utilised.

Process	Generator	Parton showering/ hadronisation	PDF
$Z/\gamma^* (\rightarrow \mu\mu) + \text{jets}$	SHERPA 1.4.1	SHERPA 1.4.1	CT10
$t\bar{t} (\geq 1\ell)$	POWHEG 1.0	PYTHIA 6.426	CT10
$WW, WZ, ZZ (\geq 1\ell)$	HERWIG 6.52	HERWIG 6.52	CTEQ6L1
Single top, $t$ -channel	AcerMC 3.8	PYTHIA 6.426	CTEQ6L1
Single top, $s$ -channel	MC@NLO 4.01	JIMMY 4.31 + HERWIG 6.52	CT10
Single top, $Wt$ -channel	MC@NLO 4.01	JIMMY 4.31 + HERWIG 6.52	CT10
$W (\rightarrow \mu\nu) + \text{jets}$	ALPGEN 2.14	JIMMY 4.31 + HERWIG 6.52	CTEQ6L1
Multi-jet	PYTHIA 8.160	PYTHIA 8.160	CT10
Signal ( $\mu\mu^* \rightarrow \mu\mu jj$ )	CompHEP 4.5.1	PYTHIA 8.170	MSTW2008lo

### 3. Signal and background simulation

Simulation of the excited-muon signal is based on calculations from [7]. Signal samples are generated at leading order (LO) with CompHEP 4.5.1 [23] using MSTW2008lo [24] parton distribution functions (PDFs). CompHEP is interfaced with PYTHIA 8.170 [25, 26] with the AU2 parameters settings [27] for the simulation of parton showers and hadronisation. Only the production of  $\mu\mu^*$  followed by the decay  $\mu^* \rightarrow \mu q\bar{q}$  is simulated. Signal samples are produced for  $\Lambda = 5$  TeV and for the  $\mu^*$  masses given in table 2. The distributions of kinematic variables should be independent of  $\Lambda$ , which was checked with generator-level studies. For a compositeness scale of  $\Lambda = 5$  TeV, cross section times branching ratios are 10.4, 2.9, and 0.21 fb for  $\mu^*$  masses of 500, 1500, and 2500 GeV, respectively. The intrinsic total width of the  $\mu^*$  is expected to be less than 8% for  $m_{\mu^*} < \Lambda$ , which is smaller than the mass resolution of about 20% over the range of  $\mu^*$  masses considered here.

The dominant background is from the process  $Z/\gamma^* \rightarrow \mu\mu$  produced in association with jets ( $Z/\gamma^* + \text{jets}$ ). The second most important background is  $t\bar{t}$  production. Other processes, such as diboson ( $WW, WZ$ , and  $ZZ$ ), single-top,  $W + \text{jets}$ , and multi-jet production, give small contributions to the background.

The  $Z/\gamma^* + \text{jets}$  samples are produced by the multi-leg LO generator SHERPA 1.4.1 [28] using CT10 [29] PDFs. The cross section for  $Z/\gamma^* \rightarrow \mu\mu$  ( $m_{\mu\mu} > 70$  GeV) plus any number of jets is 1.24 nb, calculated at next-to-leading order (NLO), corrected by a  $K$ -factor [30, 31] to next-to-next-to-leading order (NNLO) in QCD couplings and NLO in electroweak couplings. The  $t\bar{t}$  events are generated at the parton level at NLO with POWHEG 1.0 [32] and the Perugia 2011c parameter settings [33], and the parton showering is done with PYTHIA 6.426 [34]. At least one of the  $t$  or  $\bar{t}$  must have a semileptonic decay ( $e, \mu$ , or  $\tau$ ), giving a cross section for this process of 137 pb, calculated at NNLO + next-to-next-to-leading-log (NNLL) accuracy [35]. The diboson background samples are produced at LO by HERWIG 6.52 [36] with the AUET2 parameter settings [37] using CTEQ6L1 PDFs, and it is required that at least one light lepton ( $e$  or  $\mu$ ) with transverse momentum ( $p_T$ ) above 10 GeV be produced. The  $W + \text{jets}$  samples are produced by the multi-leg LO generator ALPGEN 2.14 [38] with JIMMY 4.31 [39] and HERWIG 6.52 using the AUET2 parameter settings with CTEQ6L1 PDFs, and the cross section is calculated at NNLO [30, 31]. The multi-jet samples are generated at LO by PYTHIA 8.160 using the AU2 parameter settings with CT10 PDFs. The single-top  $t$ -channel samples are generated at LO corrected to NLO + NNLL by AcerMC 3.8 [40] using the AUET2B parameters settings [41] with the CTEQ6L1 PDFs, and the parton showering is done with PYTHIA 6.426. The single-top  $s$ - and  $Wt$ -channel samples are generated at NLO with MC@NLO 4.01 [42–44] using the AUET2 parameters settings with CT10 PDFs. The background predictions from the  $Z/\gamma^* + \text{jets}$  and  $t\bar{t}$  samples are normalised using control regions discussed in section 5. Cross sections for diboson processes are evaluated at NLO [45] with an uncertainty of 5%. The  $W + \text{jets}$  and multi-jet backgrounds are determined from the Monte Carlo (MC) samples but are verified using data-driven methods. A summary of the SM samples used in this analysis is given in table 1.

The generated samples are processed using a detailed detector simulation [46] based on GEANT 4 [47] to propagate the particles through the detector material and account for the detector response. Simulated minimum-bias events are overlaid on both the signal and background samples to reproduce the effect of additional  $pp$  collisions. The simulated events are weighted to give a distribution of the number of interactions per bunch crossing that agrees with the data. The simulated background and signal events are processed with the same reconstruction programs as used for the data.

#### 4. Data set and event selection

The data were collected in 2012 during stable-beam periods of  $\sqrt{s} = 8$  TeV  $pp$  collisions. After selecting events where the relevant parts of the detector were functioning properly, the data correspond to an integrated luminosity of  $20.3 \text{ fb}^{-1}$ . The events are required to pass at least one of two single-muon triggers. The first has a nominal  $p_T$  threshold of 36 GeV, and the second has a lower nominal threshold of 24 GeV but also has an isolation requirement that the sum of the  $p_T$  of tracks with  $p_T$  above 1 GeV and within a distance of  $\Delta R = 0.2$  of the muon, excluding the muon from the sum, divided by the  $p_T$  of the muon is less than 0.12.

A primary vertex with at least three tracks with  $p_T > 0.4$  GeV within 200 mm of the centre of the detector along the beam direction is required. If there is more than one primary vertex in an event, the one with the highest sum of  $p_T^2$  is selected, where the sum is over all tracks associated with the vertex.

Each muon candidate must be reconstructed independently in both the inner detector and the muon spectrometer. Its momentum is determined by a combination of the two measurements using their covariance matrices. Only muon candidates with  $p_T^\mu$  above 30 GeV are considered. Muons must have a minimum number of hits in the inner detector and hits in each of the inner, middle, and outer layers of the muon spectrometer. These hit requirements, which restrict the muon acceptance to  $|\eta| < 2.5$ , guarantee a precise momentum measurement. To suppress background from cosmic rays, the muon tracks are required to have transverse and longitudinal impact parameters  $|d_0| < 0.2$  mm and  $|z_0| < 1$  mm with respect to the selected primary vertex. To reduce background from semileptonic decays of heavy-flavour hadrons, each muon is required to be isolated such that  $\sum p_T/p_T^\mu < 0.05$ , where the sum is over inner-detector tracks with  $p_T > 1$  GeV within a distance  $\Delta R = 0.3$  of the candidate muon, excluding the muon from the sum. The muon trigger and reconstruction efficiencies are evaluated using tag-and-probe techniques with  $Z \rightarrow \mu\mu$  events [48, 49], and  $p_T$ - and  $\eta$ -dependent corrections are applied to simulated events. Events are required to have exactly two muons of opposite charge that meet these selection requirements.

Although electrons are not part of the signal for this search, they are used to define one of the control regions (see section 5). Each electron candidate is formed from the energy in a cluster of cells in the electromagnetic calorimeter associated with a charged-particle track in the inner detector. Each electron must have  $p_T$  above 30 GeV and have  $|\eta| < 2.47$  but not be in the interval  $1.37 < |\eta| < 1.52$  to avoid the transition region between the barrel and endcap calorimeters. The ATLAS tight electron identification criteria (based on the methodology described in [50] and updated for 2012 running conditions) for the transverse shower shape, longitudinal leakage into the hadronic calorimeter, the association with an inner-detector track, and hits in the transition radiation detector are applied to the cluster. An electron track is required to have transverse and longitudinal impact parameters  $|d_0| < 1$  mm and  $|z_0| < 5$  mm with respect to the selected primary vertex. Finally, the electrons must pass the isolation requirement  $\sum E_T < 0.007E_T^e + 5$  GeV, where the sum is of transverse energies deposited in cells within a cone of  $\Delta R = 0.2$  around the electron, excluding those cells associated with the electron, and  $E_T^e$  is the transverse energy of the electron.

Jets of hadrons are reconstructed using the anti- $k_t$  algorithm [51] with a radius parameter of  $R = 0.4$  applied to clusters of calorimeter cells that are topologically connected. The jets are calibrated using energy- and  $\eta$ -dependent correction factors derived from simulation and with residual corrections from *in situ* measurements [52]. Jets are required to have  $|\eta| < 2.8$  and  $p_T > 30$  GeV. Jets that overlap ( $\Delta R < 0.4$ ) any electron or muon candidate satisfying the selection criteria described above are removed. The two jets with the highest  $p_T$  are then selected.

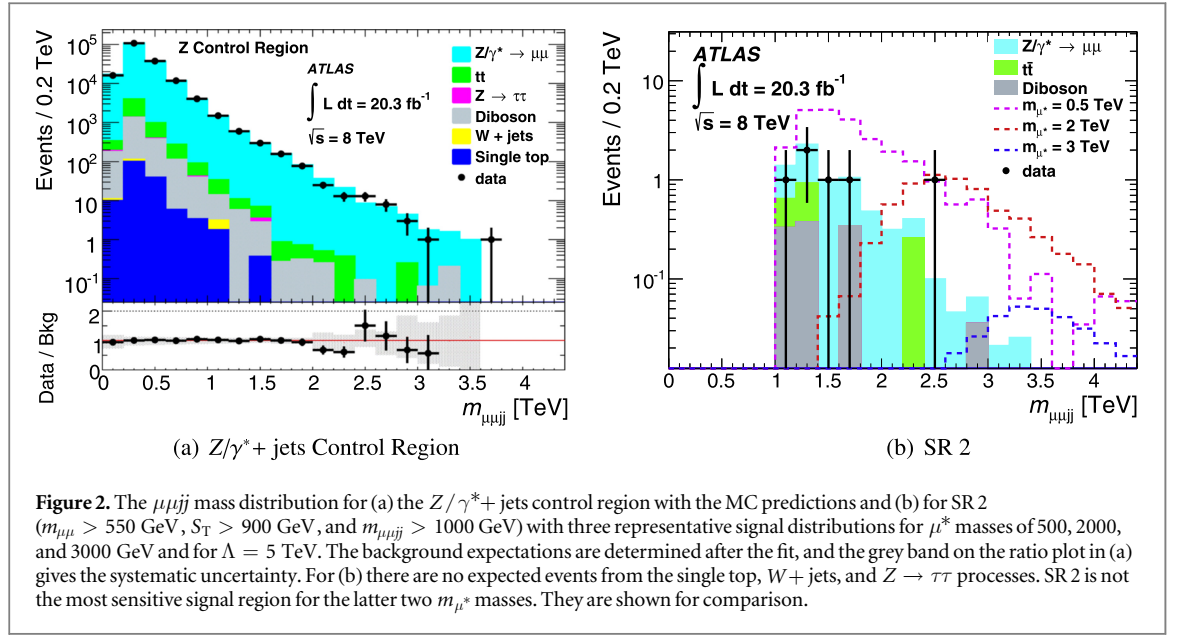
The missing transverse momentum vector is the negative of the vector sum of the transverse momenta of muons, electrons, photons [53], jets, and clusters of calibrated calorimeter cells not associated with these objects. The missing transverse energy is the magnitude of the missing transverse momentum vector.

#### 5. Background determination

Most of the SM background contributions are estimated from the MC samples. The expected yields from the  $Z/\gamma^* +$  jets and  $t\bar{t}$  production processes are normalised to the data using control regions. The  $Z/\gamma^* +$  jets control region is defined by  $70 < m_{\mu\mu} < 110$  GeV in addition to the selection criteria given in section 4. The  $t\bar{t}$  control region is defined as events that meet the selection requirements given in section 4, except there is exactly one muon and one electron of opposite sign, so it should contain no signal events. The normalisation scale factors are determined from simultaneous fits to data in the control and signal regions (SRs) (see section 8). The scale factors are primarily determined from the control regions, giving the same values in all cases. From the fits, the scale factor is  $1.010^{+0.087}_{-0.066}$  for the  $Z/\gamma^* +$  jets sample and is  $1.050 \pm 0.013$  for the  $t\bar{t}$  sample. The MC predictions agree well with the data in the control regions, as can be seen, for example, in figure 2(a).

A jet can produce a prompt muon candidate either from the semileptonic decay of a heavy quark or from misidentification of a charged hadron in the jet as a muon. The expected background from jets, primarily from





$W + \text{jets}$  and multi-jet processes, is determined from MC samples, giving zero expected events. This prediction is checked by the data-driven matrix method [54], which uses isolated and non-isolated muons and their data-determined efficiencies and misidentification rates to determine the number of prompt muons. The matrix method predicts  $-0.07 \pm 0.55$  events from these backgrounds.

## 6. Signal regions

SRs are defined by three kinematic variables—the dimuon invariant mass  $m_{\mu\mu}$ , the invariant mass  $m_{\mu\mu jj}$  of the two muons and two jets ( $j$ ), and  $S_T$ , the scalar sum of transverse momenta of the four signal objects, that is<sup>272</sup>,  $S_T = p_T^{\mu 1} + p_T^{\mu 2} + p_T^{j1} + p_T^{j2}$ .

For all three of these variables, the signal tends to have higher values than the backgrounds, so all criteria are lower bounds in the selection. The values of these bounds are chosen to maximise the search sensitivity for each signal mass considered by scanning the three-dimensional parameter space for the values that minimize the expected 95% confidence level (CL) upper limit on the cross section times branching ratio. The selection criteria for the SRs are shown in table 2. The  $m_{\mu\mu jj}$  and  $S_T$  criteria increase with increasing signal mass, but the  $m_{\mu\mu}$  criterion decreases. The latter is because the increase in the other parameters sufficiently reduces the expected background so that the signal efficiency may be increased by decreasing the  $m_{\mu\mu}$  criterion.

The dominant background in all SRs is from the  $Z/\gamma^* + \text{jets}$  process, which is 50% of the background in SR 1, rising to 90% or more in SR 5 through SR 10. The  $t\bar{t}$  process contributes 40% of the background in SR 1, but this contribution falls quickly to 10% or less in SR 3 through SR 10. The contribution to the background from all other processes is between 10% and 20% in SR 1 through SR 5 and is less than 5% for SR 6 through SR 10.

## 7. Systematic uncertainties

Contributions to the systematic uncertainties in the background and signal yield predictions stem from both experimental and theoretical sources, as discussed below.

The luminosity is derived using the methodology in [55] and has an uncertainty of 2.8%. The luminosity uncertainty for the backgrounds is less than this because the largest backgrounds ( $Z/\gamma^* + \text{jets}$  and  $t\bar{t}$ ) are normalised using control regions.

Uncertainties in the MC modelling of the detector, particularly for muons and jets in this analysis, must be taken into account and are derived from detailed studies of data. One-standard-deviation variation of a given parameter is determined, and then the parameter is varied up and down in the simulation by this amount to determine the effect on the signal and background yields.

<sup>272</sup> The  $\mu jj$  invariant mass was considered as a discriminating variable instead of one of the three selection variables. Several methods for selecting the correct  $\mu jj$  combination and the possibility of using both  $\mu jj$  combinations were considered. No method that improved the sensitivity was found.

**Table 2.** The signal masses considered and the corresponding signal regions are listed. The  $m_{\mu\mu}$ ,  $S_T$ , and  $m_{\mu\mu jj}$  values giving the lower bound of each signal region are listed, along with the acceptance times efficiency, the expected number of signal events ( $\Lambda = 5$  TeV), expected number of background events before and after the fit discussed in section 8, and the number of events observed in the data. The uncertainties in the expected numbers of signal and background events are the systematic uncertainties. The numbers of events observed are discussed in section 8.

$m_{\mu^*}$ (GeV)	Signal region	$m_{\mu\mu}$ (GeV)	$S_T$ (GeV)	$m_{\mu\mu jj}$ (GeV)	Acc $\times$ Eff	Exp signal	Exp BG (prefit)	Exp BG (postfit)	Obs events
100	1	500	450	0	0.041	$3.0 \pm 0.3$	$73 \pm 17$	$71.7 \pm 8.6$	71
300	2	550	900	1000	0.088	$12.5 \pm 0.9$	$10.1 \pm 3.5$	$7.8 \pm 2.2$	6
500	2	550	900	1000	0.15	$29.4 \pm 1.6$	$10.1 \pm 3.5$	$7.8 \pm 2.2$	6
750	3	450	900	1300	0.23	$43.7 \pm 2.2$	$6.6 \pm 2.5$	$5.8 \pm 1.9$	5
1000	4	450	1050	1300	0.31	$44.1 \pm 1.8$	$4.6 \pm 1.8$	$4.6 \pm 1.9$	5
1250	5	450	1200	1500	0.38	$29.8 \pm 1.3$	$2.1 \pm 0.9$	$2.1 \pm 1.0$	3
1500	6	400	1200	1700	0.38	$19.8 \pm 0.8$	$1.5 \pm 0.7$	$1.3 \pm 0.6$	1
1750	7	300	1350	1900	0.41	$11.8 \pm 0.5$	$0.9 \pm 0.7$	$0.9 \pm 0.5$	2
2000	8	300	1350	2000	0.40	$6.6 \pm 0.2$	$0.7 \pm 0.4$	$0.7 \pm 0.4$	2
2250	9	300	1500	2100	0.37	$3.4 \pm 0.1$	$0.4 \pm 0.3$	$0.4 \pm 0.3$	2
2500	10	110	1650	2300	0.39	$1.65 \pm 0.07$	$0.2^{+1.3}_{-0.2}$	$0.2^{+1.0}_{-0.2}$	2
2750	10	110	1650	2300	0.45	$0.72 \pm 0.02$	$0.2^{+1.3}_{-0.2}$	$0.2^{+1.0}_{-0.2}$	2
2900	10	110	1650	2300	0.45	$0.52 \pm 0.02$	$0.2^{+1.3}_{-0.2}$	$0.2^{+1.0}_{-0.2}$	2
3000	10	110	1650	2300	0.46	$0.38 \pm 0.02$	$0.2^{+1.3}_{-0.2}$	$0.2^{+1.0}_{-0.2}$	2
3100	10	110	1650	2300	0.45	$0.30 \pm 0.02$	$0.2^{+1.3}_{-0.2}$	$0.2^{+1.0}_{-0.2}$	2

**Table 3.** Largest contributions to the relative systematic uncertainty in the signal yield. The uncertainties for the hadronisation and factorisation scales and for the PDFs are only for the signal acceptance times efficiency. All uncertainties are given in percent and are determined after the fit discussed in section 8.

$m_{\mu^*}$ (GeV)	500	1500	2500
Luminosity	2.8	2.8	2.8
Jet energy scale	2.7	1.5	1.1
Hadronisation and factorisation scales	2.0	0.5	0.1
PDFs	3.0	2.5	2.7
Muon efficiency	0.7	0.8	0.9
Jet energy resolution	0.9	0.2	0.5
Muon spectrometer resolution	0.3	<0.1	0.2
Total	5.1	4.1	4.2

The uncertainty in the jet energy scale is the largest contribution to the systematic uncertainty in the signal yield and a significant contribution to the uncertainty in the backgrounds. The uncertainty in the jet energy resolution also makes a contribution. These uncertainties are determined from  $p_T$  balance in  $\gamma + \text{jet}$  and  $Z + \text{jet}$  events and in events with high- $p_T$  jets recoiling against multiple, low- $p_T$  jets [52, 56]. The uncertainty in contributions from additional energy deposited in the calorimeters from other  $pp$  interactions in the event is also included. The various effects are investigated separately and combined to give the values summarised in tables 3 and 4.

Muon performance is determined in  $Z \rightarrow \mu\mu$  events. The most important parameters for this analysis are the muon efficiency and the muon spectrometer  $p_T$  resolution. The inner-detector resolution and the muon  $p_T$  scale are found to have negligible effect. The uncertainty in the trigger efficiency is less than 2% for the backgrounds and less than 1% for the signal yield.

The uncertainties in the signal and background yield predictions due to uncertainties in PDFs have two contributions. The first is from one-standard-deviation variation of the parameters of the relevant PDFs (section 3). The second is a comparison with the alternative NNPDF2.1 PDF set [57]. These variations produce changes in the predicted cross section and in kinematical distributions, which in turn affect the acceptance times efficiency. For the background, both effects are included in the systematic uncertainty. For the signal yield, the uncertainty in the acceptance times efficiency is included, but the uncertainty in the cross section is considered part of the uncertainty in the theoretical prediction and is not included in the statistical analysis.

The uncertainty in the background modelling in the SRs is estimated by examining how well the MC prediction agrees with the data in two validation regions selected to be similar in kinematics to the SRs but



**Table 4.** Largest contributions to the relative systematic uncertainty in the expected background for three representative signal regions. All uncertainties are given in percent and are determined after the fit discussed in section 8.

Signal region	2	6	10
$Z/\gamma^* + \text{jets modelling}$	25	47	65
Jet energy scale	19	9.0	6.2
$t\bar{t}$ modelling	12	<0.1	<0.1
Muon spectrometer resolution	6.2	0.6	63
PDFs	4.2	8.8	17
Jet energy resolution	3.2	1.7	0.6
Muon efficiency	0.7	0.8	0.9
Luminosity	0.4	0.1	<0.1
$Z/\gamma^* + \text{jets extrapolation}$	—	—	500
Total	35	49	500

containing no signal. Both validation regions require the same selection as the SRs except that  $m_{\mu\mu jj} < 500$  GeV and  $m_{\mu\mu} > 200$  GeV with no selection on  $S_T$ . Requiring the missing transverse energy be greater (less) than 50 GeV (40 GeV) selects a validation region dominated by  $t\bar{t}$  ( $Z/\gamma^*$ ) events. For some of the kinematic variables, an extrapolation of the predicted yield from the validation regions to the SRs is necessary to evaluate possible mismodelling effects. Of the several kinematic variables studied, only the modelling of the  $S_T$  variable is found to have a significant effect. A linear fit to the ratio of the number of data events to the MC expectation is extrapolated to higher values of  $S_T$ , and the deviation from unity symmetrized about zero gives the uncertainty, referred to as ‘ $Z/\gamma^* + \text{jets modelling}$ ’ and ‘ $t\bar{t}$  modelling’ in table 4. For both validation regions, the linear fit is consistent within the statistical uncertainties with a flat line at a ratio of one.

To produce sufficient numbers of events for high dimuon masses, the  $Z/\gamma^*$  MC samples were produced in bins of dimuon mass above the  $Z$  mass. For the  $S_T$  and  $m_{\mu\mu jj}$  criteria in this analysis, this yields zero events in SR 7 through SR 10 for some ranges of the  $m_{\mu\mu}$  distribution (for example, 110 to 400 GeV for SR 10). For these SRs, an additional systematic uncertainty (referred to as ‘ $Z/\gamma^* + \text{jets extrapolation}$ ’ in table 4) is estimated by loosening the  $S_T$  criteria and extrapolating into the SR. The uncertainty introduced by this procedure is small except in SR 10, where the effect on the statistical analysis is still small because the predicted number of background events is only 0.2.

Additional sources of uncertainty in the acceptance times efficiency are initial-state radiation, final-state radiation, renormalisation and factorisation scales, and the beam energy. The effects of initial- and final-state radiation are determined in generator-level studies by varying the relevant PYTHIA parameters and are less than 1%. The effect of the beam energy uncertainty (0.65%) [58] is determined by varying the momentum fraction of the initial partons in the PDFs by this amount, giving a change of less than 1%. The renormalisation and factorisation scales are independently varied in the simulation by factors of 2 and 1/2, changing the expected signal acceptance times efficiency by about 2% at low mass and by less than 1% for masses above 750 GeV.

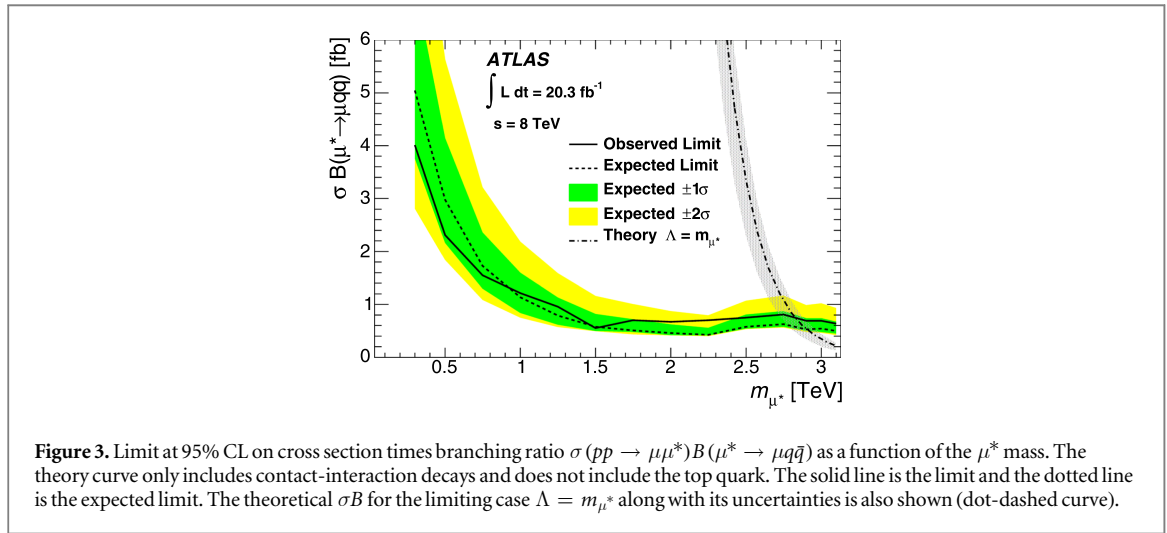
The uncertainties in the signal yield depend on the  $\mu^*$  mass, and the largest contributions are summarised in table 3 for three representative masses. For the signal yield, uncertainties in jet energy scale, PDFs, and luminosity are the dominant sources. The uncertainties in the background depend on the SR, and the largest contributions are shown in table 4 for three representative regions. The most significant contributions to the background uncertainty are from the modelling of the  $Z/\gamma^* + \text{jets}$  and  $t\bar{t}$  processes. The jet energy scale and the parton distribution functions also make significant contributions. Any source of systematic uncertainty contributing less than 2% to the background for all SRs and less than 1% to the signal yield for all  $\mu^*$  masses would have negligible effect in the statistical analysis in section 8 and is not included.

## 8. Results

For each  $\mu^*$  mass considered, the numbers of events in the corresponding SR and in the two control regions are simultaneously fit [59] using a profile likelihood method [60, 61]. The likelihood function models the number of events as a Poisson distribution and the systematic effects are modelled using nuisance parameters with lognormal constraints. The parameters of interest in the fit are the signal yield in the corresponding SR and the normalisations of the  $Z/\gamma^*$  and  $t\bar{t}$  backgrounds, with the latter two being primarily determined in the fit by the events in the control regions. The possible contribution of signal to the control regions is included in the fit and found to be negligible. Correlations of the systematic uncertainties are taken into account.

**Table 5.** Values of  $\mu\mu$  mass,  $\mu\mu jj$  mass,  $S_T$ ,  $\mu jj$  mass for each  $\mu jj$  combination, and  $p_T$  of each muon and jet for the three events in SR 9 or 10.

Event	SR	$m_{\mu\mu}$ (GeV)	$m_{\mu\mu jj}$ (GeV)	$S_T$ (GeV)	$m_{\mu_1 jj}$ (GeV)	$m_{\mu_2 jj}$ (GeV)	$p_T^{\mu_1}$ (GeV)	$p_T^{\mu_2}$ (GeV)	$p_T^{j_1}$ (GeV)	$p_T^{j_2}$ (GeV)
A	all	1800	2410	1820	1200	1090	650	630	350	190
B	7–9	310	2250	2010	2200	630	840	46	990	130
C	10	113	2440	1760	2230	1850	150	35	890	690

**Figure 3.** Limit at 95% CL on cross section times branching ratio  $\sigma(pp \rightarrow \mu\mu^*)B(\mu^* \rightarrow \mu q\bar{q})$  as a function of the  $\mu^*$  mass. The theory curve only includes contact-interaction decays and does not include the top quark. The solid line is the limit and the dotted line is the expected limit. The theoretical  $\sigma B$  for the limiting case  $\Lambda = m_{\mu^*}$  along with its uncertainties is also shown (dot-dashed curve).

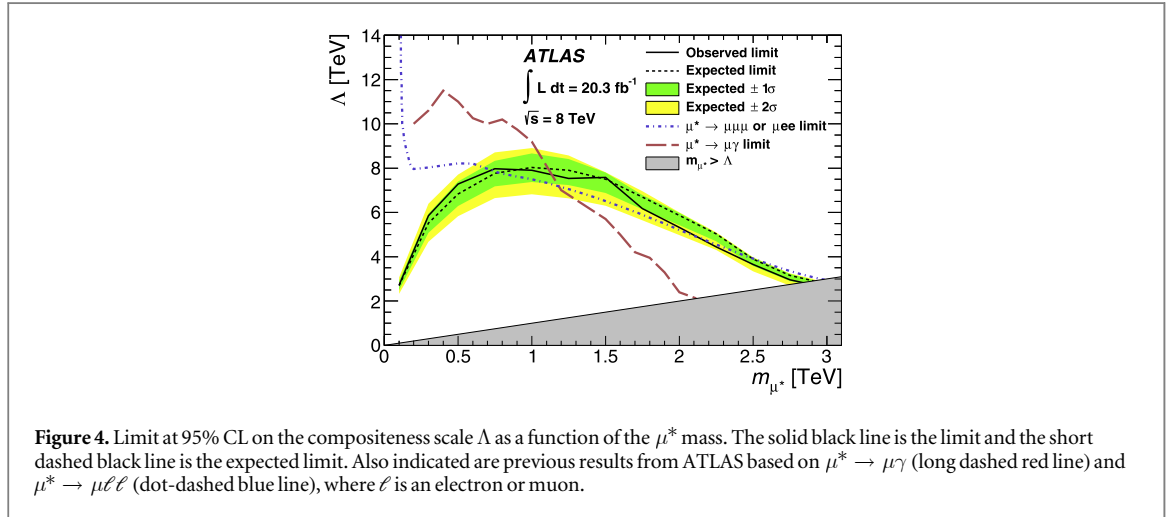
As an example of the result of the fit, the  $m_{\mu\mu jj}$  distribution for SR 2 is shown in figure 2(b) for the data, expected backgrounds, and three signal predictions for  $\Lambda = 5$  TeV (the SRs for the higher masses have fewer background events). The expected and observed numbers of events for each signal mass considered are shown in table 2 for  $\Lambda = 5$  TeV. Due to correlations among the nuisance parameters, the uncertainties on the expected backgrounds are reduced after the fits. The data are consistent with the SM expectations, and no significant excess is observed. Thus, limits on the cross section times branching ratio as a function of the  $\mu^*$  mass are calculated.

A modified frequentist  $CL_s$  method [62, 63] is used to derive the 95% CL upper limits on the signal yield. The expected limit is the median limit for a large number of background-only pseudo-experiments. The one- and two-standard-deviations bands cover 68% and 95%, respectively, of the pseudo-experiment limits. The observed limit is the 95% CL limit for the observed number of events. The  $p$ -value is a measure of how well the background-only hypothesis models the data. For a SR, it is the fraction of background-only pseudo-experiments where the fitted signal value is greater than that for the observed data.

The smallest  $p$ -values are for SR 9 and 10 with values of 0.034 and 0.099, respectively, corresponding to 1.8 and 1.3 standard deviations on one side of a Gaussian distribution. Some kinematic properties of the events in these SRs are given in table 5. There is one event (event A) that is in all SRs.

An upper limit on the cross section times branching ratio  $\sigma(pp \rightarrow \mu\mu^*) \times B(\mu^* \rightarrow \mu q\bar{q})$  (figure 3) is determined for each signal mass from the limit on the signal yield at the 95% CL. The theoretical uncertainties are not included in either the  $\sigma B$  or  $\Lambda$  limit determinations. For  $m_{\mu^*}$  above 1.3 TeV, the limit is between 0.6 and 1 fb. The theoretical expectation for  $\Lambda = m_{\mu^*}$  is also shown. The theoretical band represents uncertainties from PDFs and from renormalisation and factorisation scales.

The expected cross section and branching ratio depend on the  $\mu^*$  mass and on  $\Lambda$  [7]. For each signal mass, the limit on  $\sigma B$  is translated into a lower bound on the compositeness scale (figure 4). The bound is the value of  $\Lambda$  for which the theoretical prediction of  $\sigma B(m_{\mu^*}, \Lambda)$  is equal to the upper limit on  $\sigma B$ . The region with  $m_{\mu^*} > \Lambda$  is unphysical. For the limiting case where  $\Lambda = m_{\mu^*}$ , excited-muon masses below 2.8 TeV are excluded. Previous limits set by ATLAS [17, 21] are also shown. The analysis presented here improves upon the limits from  $\mu^* \rightarrow \mu\gamma$  for masses above 1100 GeV and upon those from  $\mu^* \rightarrow \mu\ell\ell$  for masses from 700 to 2100 GeV.



## 9. Conclusion

The results of a search for excited muons decaying to  $\mu jj$  via a contact interaction are reported based on data from  $\sqrt{s} = 8$  TeV  $pp$  collisions collected with the ATLAS detector at the LHC corresponding to an integrated luminosity of  $20.3 \text{ fb}^{-1}$ . The observed data are consistent with SM expectations. An upper limit is set at 95% CL on the cross section times branching ratio  $\sigma B(\mu^* \rightarrow \mu q \bar{q})$  as a function of the excited-muon mass. For  $m_{\mu^*}$  between 1.3 and 3.0 TeV, the limit on  $\sigma B$  is between 0.6 and 1 fb.

The  $\sigma B$  upper limits are converted to lower bounds on the compositeness scale  $\Lambda$ . In the limiting case where  $\Lambda = m_{\mu^*}$ , excited-muon masses below 2.8 TeV are excluded. At higher  $\mu^*$  masses, the signature explored in this paper,  $\mu^* \rightarrow \mu j j$ , has better sensitivity than the traditional signature  $\mu^* \rightarrow \mu \gamma$ . For  $\mu^*$  masses above 0.8 TeV, the sensitivity is up to 15% better than a previous search using the signature  $\mu^* \rightarrow \mu \ell \ell$ . In models other than the benchmark model used here, the branching ratios to these modes could be different, affecting their relative importance for limits on the compositeness scale.

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## The ATLAS Collaboration

G Aad<sup>85</sup>, B Abbott<sup>112</sup>, J Abdallah<sup>150</sup>, O Abidinov<sup>11</sup>, B Abeloos<sup>116</sup>, R Aben<sup>106</sup>, M Abolins<sup>90</sup>, O S AbouZeid<sup>157</sup>, H Abramowicz<sup>152</sup>, H Abreu<sup>151</sup>, R Abreu<sup>115</sup>, Y Abulaiti<sup>145a,145b</sup>, B S Acharya<sup>163a,163b,178</sup>, L Adamczyk<sup>38a</sup>,

D L Adams<sup>25</sup>, J Adelman<sup>107</sup>, S Adomeit<sup>99</sup>, T Adye<sup>130</sup>, A A Affolder<sup>74</sup>, T Agatonovic-Jovin<sup>13</sup>, J Agricola<sup>54</sup>, J A Aguilar-Saavedra<sup>125a,125f</sup>, S P Ahlen<sup>22</sup>, F Ahmadov<sup>65,179</sup>, G Aielli<sup>132a,132b</sup>, H Akerstedt<sup>145a,145b</sup>, T P A Åkesson<sup>81</sup>, A V Akimov<sup>95</sup>, G L Alberghi<sup>20a,20b</sup>, J Albert<sup>168</sup>, S Albrand<sup>55</sup>, M J Alconada Verzini<sup>71</sup>, M Aleksa<sup>30</sup>, I N Aleksandrov<sup>65</sup>, C Alexa<sup>26b</sup>, G Alexander<sup>152</sup>, T Alexopoulos<sup>10</sup>, M Alhroob<sup>112</sup>, G Alimonti<sup>91a</sup>, L Alio<sup>85</sup>, J Alison<sup>31</sup>, S P Alkire<sup>35</sup>, B M M Allbrooke<sup>148</sup>, B W Allen<sup>115</sup>, P P Allport<sup>18</sup>, A Aloisio<sup>103a,103b</sup>, A Alonso<sup>36</sup>, F Alonso<sup>71</sup>, C Alpigiani<sup>137</sup>, B Alvarez Gonzalez<sup>30</sup>, D Álvarez 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H Wahlberg<sup>71</sup>, S Wahrmund<sup>44</sup>, J Wakabayashi<sup>102</sup>, J Walder<sup>72</sup>, R Walker<sup>99</sup>, W Walkowiak<sup>140</sup>,  
V Wallangen<sup>145a,145b</sup>, C Wang<sup>150</sup>, C Wang<sup>33d,85</sup>, F Wang<sup>172</sup>, H Wang<sup>15</sup>, H Wang<sup>40</sup>, J Wang<sup>42</sup>, J Wang<sup>149</sup>,  
K Wang<sup>87</sup>, R Wang<sup>6</sup>, S M Wang<sup>150</sup>, T Wang<sup>21</sup>, T Wang<sup>35</sup>, X Wang<sup>175</sup>, C Wanotayaroj<sup>115</sup>, A Warburton<sup>87</sup>,  
C P Ward<sup>28</sup>, D R Wardrope<sup>78</sup>, A Washbrook<sup>46</sup>, P M Watkins<sup>18</sup>, A T Watson<sup>18</sup>, I J Watson<sup>149</sup>, M F Watson<sup>18</sup>,  
G Watts<sup>137</sup>, S Watts<sup>84</sup>, B M Waugh<sup>78</sup>, S Webb<sup>84</sup>, M S Weber<sup>17</sup>, S W Weber<sup>173</sup>, J S Webster<sup>6</sup>, A R Weidberg<sup>119</sup>,  
B Weinert<sup>61</sup>, J Weingarten<sup>54</sup>, C Weiser<sup>48</sup>, H Weits<sup>106</sup>, P S Wells<sup>30</sup>, T Wenaus<sup>25</sup>, T Wengler<sup>30</sup>, S Wenig<sup>30</sup>,  
N Vermes<sup>21</sup>, M Werner<sup>48</sup>, P Werner<sup>30</sup>, M Wessels<sup>58a</sup>, J Wetter<sup>160</sup>, K Whalen<sup>115</sup>, A M Wharton<sup>72</sup>, A White<sup>8</sup>,  
M J White<sup>1</sup>, R White<sup>32b</sup>, S White<sup>123a,123b</sup>, D Whiteson<sup>162</sup>, F J Wickens<sup>130</sup>, W Wiedenmann<sup>172</sup>, M Wielers<sup>130</sup>,  
P Wienemann<sup>21</sup>, C Wigglesworth<sup>36</sup>, L A M Wiik-Fuchs<sup>21</sup>, A Wildauer<sup>100</sup>, H G Wilkens<sup>30</sup>, H H Williams<sup>121</sup>,  
S Williams<sup>106</sup>, C Willis<sup>90</sup>, S Willocq<sup>86</sup>, J A Wilson<sup>18</sup>, I Wingerter-Seez<sup>5</sup>, F Winklmeier<sup>115</sup>, B T Winter<sup>21</sup>,  
M Wittgen<sup>142</sup>, J Wittkowski<sup>99</sup>, S J Wollstadt<sup>83</sup>, M W Wolter<sup>39</sup>, H Wolters<sup>125a,125c</sup>, B K Wosiek<sup>39</sup>, J Wotschack<sup>30</sup>,  
M J Woudstra<sup>84</sup>, K W Wozniak<sup>39</sup>, M Wu<sup>55</sup>, M Wu<sup>31</sup>, S L Wu<sup>172</sup>, X Wu<sup>49</sup>, Y Wu<sup>89</sup>, T R Wyatt<sup>84</sup>, B M Wynne<sup>46</sup>,  
S Xella<sup>36</sup>, D Xu<sup>33a</sup>, L Xu<sup>25</sup>, B Yabsley<sup>149</sup>, S Yacoub<sup>144a</sup>, R Yakabe<sup>67</sup>, D Yamaguchi<sup>156</sup>, Y Yamaguchi<sup>117</sup>,  
A Yamamoto<sup>66</sup>, S Yamamoto<sup>154</sup>, T Yamanaka<sup>154</sup>, K Yamauchi<sup>102</sup>, Y Yamazaki<sup>67</sup>, Z Yan<sup>22</sup>, H Yang<sup>33c</sup>,  
H Yang<sup>172</sup>, Y Yang<sup>150</sup>, Z Yang<sup>14</sup>, W-M Yao<sup>15</sup>, Y C Yap<sup>80</sup>, Y Yasu<sup>66</sup>, E Yatsenko<sup>5</sup>, K H Yau Wong<sup>21</sup>, J Ye<sup>40</sup>, S Ye<sup>25</sup>,  
I Yeletsikh<sup>65</sup>, A L Yen<sup>57</sup>, E Yildirim<sup>42</sup>, K Yorita<sup>170</sup>, R Yoshida<sup>6</sup>, K Yoshihara<sup>121</sup>, C Young<sup>142</sup>, C J S Young<sup>30</sup>,  
S Youssef<sup>22</sup>, D R Yu<sup>15</sup>, J Yu<sup>8</sup>, J M Yu<sup>89</sup>, J Yu<sup>64</sup>, L Yuan<sup>67</sup>, S P Y Yuen<sup>21</sup>, I Yusuff<sup>28,217</sup>, B Zabinski<sup>39</sup>, R Zaidan<sup>33d</sup>,  
A M Zaitsev<sup>129,207</sup>, N Zakharchuk<sup>42</sup>, J Zalieckas<sup>14</sup>, A Zaman<sup>147</sup>, S Zambito<sup>57</sup>, L Zanello<sup>131a,131b</sup>, D Zanzi<sup>88</sup>,  
C Zeitnitz<sup>174</sup>, M Zeman<sup>127</sup>, A Zemla<sup>38a</sup>, J C Zeng<sup>164</sup>, Q Zeng<sup>142</sup>, K Zengel<sup>23</sup>, O Zenin<sup>129</sup>, T Ženiš<sup>143a</sup>, D Zerwas<sup>116</sup>,  
D Zhang<sup>89</sup>, F Zhang<sup>172</sup>, G Zhang<sup>33b,204</sup>, H Zhang<sup>33c</sup>, J Zhang<sup>6</sup>, L Zhang<sup>48</sup>, R Zhang<sup>21</sup>, R Zhang<sup>33b,218</sup>, X Zhang<sup>33d</sup>,  
Z Zhang<sup>116</sup>, X Zhao<sup>40</sup>, Y Zhao<sup>33d,116</sup>, Z Zhao<sup>33b</sup>, A Zhemchugov<sup>65</sup>, J Zhong<sup>119</sup>, B Zhou<sup>89</sup>, C Zhou<sup>45</sup>, L Zhou<sup>35</sup>,  
L Zhou<sup>40</sup>, M Zhou<sup>147</sup>, N Zhou<sup>33f</sup>, C G Zhu<sup>33d</sup>, H Zhu<sup>33a</sup>, J Zhu<sup>89</sup>, Y Zhu<sup>33b</sup>, X Zhuang<sup>33a</sup>, K Zhukov<sup>95</sup>, A Zibell<sup>173</sup>,  
D Zieminska<sup>61</sup>, N I Zimine<sup>65</sup>, C Zimmermann<sup>83</sup>, S Zimmermann<sup>48</sup>, Z Zinonos<sup>54</sup>, M Zinser<sup>83</sup>, M Ziolkowski<sup>140</sup>,  
L Živković<sup>13</sup>, G Zobernig<sup>172</sup>, A Zoccoli<sup>20a,20b</sup>, M zur Nedden<sup>16</sup>, G Zurzolo<sup>103a,103b</sup>, L Zwalinski<sup>30</sup> The ATLAS  
Collaboration

<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany NY, USA

<sup>3</sup> Department of Physics, University of Alberta, Edmonton AB, Canada

<sup>4a</sup> Department of Physics, Ankara University, Ankara, Turkey

<sup>4b</sup> Istanbul Aydin University, Istanbul, Turkey

<sup>4c</sup> Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

<sup>5</sup> LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France

<sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL, USA

<sup>7</sup> Department of Physics, University of Arizona, Tucson AZ, USA

<sup>8</sup> Department of Physics, The University of Texas at Arlington, Arlington TX, USA

<sup>9</sup> Physics Department, University of Athens, Athens, Greece

<sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece

<sup>11</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>12</sup> Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain

<sup>13</sup> Institute of Physics, University of Belgrade, Belgrade, Serbia

<sup>14</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>15</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, USA

<sup>16</sup> Department of Physics, Humboldt University, Berlin, Germany

<sup>17</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

<sup>18</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, UK

<sup>19a</sup> Department of Physics, Bogazici University, Istanbul, Turkey

<sup>19b</sup> Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

<sup>19c</sup> Department of Physics, Dogus University, Istanbul, Turkey

<sup>20a</sup> INFN Sezione di Bologna, Italy

<sup>20b</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

<sup>21</sup> Physikalisches Institut, University of Bonn, Bonn, Germany

<sup>22</sup> Department of Physics, Boston University, Boston MA, USA

<sup>23</sup> Department of Physics, Brandeis University, Waltham MA, USA

<sup>24a</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil

<sup>24b</sup> Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil

<sup>24c</sup> Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil

<sup>24d</sup> Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil

<sup>25</sup> Physics Department, Brookhaven National Laboratory, Upton NY, USA

<sup>26a</sup> Transilvania University of Brasov, Brasov, Romania

<sup>26b</sup> National Institute of Physics and Nuclear Engineering, Bucharest, Romania

<sup>26c</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania

- <sup>26d</sup> University Politehnica Bucharest, Bucharest, Romania
- <sup>26e</sup> West University in Timisoara, Timisoara, Romania
- <sup>27</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- <sup>28</sup> Cavendish Laboratory, University of Cambridge, Cambridge, UK
- <sup>29</sup> Department of Physics, Carleton University, Ottawa ON, Canada
- <sup>30</sup> CERN, Geneva, Switzerland
- <sup>31</sup> Enrico Fermi Institute, University of Chicago, Chicago IL, USA
- <sup>32a</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
- <sup>32b</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>33a</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, People's Republic of China
- <sup>33b</sup> Department of Modern Physics, University of Science and Technology of China, Anhui, People's Republic of China
- <sup>33c</sup> Department of Physics, Nanjing University, Jiangsu, People's Republic of China
- <sup>33d</sup> School of Physics, Shandong University, Shandong, People's Republic of China
- <sup>33e</sup> Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, People's Republic of China
- <sup>33f</sup> Physics Department, Tsinghua University, Beijing 100084, People's Republic of China
- <sup>34</sup> Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- <sup>35</sup> Nevis Laboratory, Columbia University, Irvington NY, USA
- <sup>36</sup> Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- <sup>37a</sup> INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
- <sup>37b</sup> Dipartimento di Fisica, Università della Calabria, Rende, Italy
- <sup>38a</sup> AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
- <sup>38b</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- <sup>39</sup> Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- <sup>40</sup> Physics Department, Southern Methodist University, Dallas TX, USA
- <sup>41</sup> Physics Department, University of Texas at Dallas, Richardson TX, USA
- <sup>42</sup> DESY, Hamburg and Zeuthen, Germany
- <sup>43</sup> Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- <sup>44</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- <sup>45</sup> Department of Physics, Duke University, Durham NC, USA
- <sup>46</sup> SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK
- <sup>47</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>48</sup> Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- <sup>49</sup> Section de Physique, Université de Genève, Geneva, Switzerland
- <sup>50a</sup> INFN Sezione di Genova, Italy
- <sup>50b</sup> Dipartimento di Fisica, Università di Genova, Genova, Italy
- <sup>51a</sup> E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
- <sup>51b</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- <sup>52</sup> II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- <sup>53</sup> SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, UK
- <sup>54</sup> II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- <sup>55</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- <sup>56</sup> Department of Physics, Hampton University, Hampton VA, USA
- <sup>57</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, USA
- <sup>58a</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>58b</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>58c</sup> ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- <sup>59</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- <sup>60a</sup> Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, People's Republic of China
- <sup>60b</sup> Department of Physics, The University of Hong Kong, Hong Kong, People's Republic of China
- <sup>60c</sup> Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- <sup>61</sup> Department of Physics, Indiana University, Bloomington IN, USA
- <sup>62</sup> Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- <sup>63</sup> University of Iowa, Iowa City IA, USA
- <sup>64</sup> Department of Physics and Astronomy, Iowa State University, Ames IA, USA
- <sup>65</sup> Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- <sup>66</sup> KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- <sup>67</sup> Graduate School of Science, Kobe University, Kobe, Japan
- <sup>68</sup> Faculty of Science, Kyoto University, Kyoto, Japan
- <sup>69</sup> Kyoto University of Education, Kyoto, Japan
- <sup>70</sup> Department of Physics, Kyushu University, Fukuoka, Japan
- <sup>71</sup> Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- <sup>72</sup> Physics Department, Lancaster University, Lancaster, UK
- <sup>73a</sup> INFN Sezione di Lecce, Italy
- <sup>73b</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- <sup>74</sup> Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK
- <sup>75</sup> Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- <sup>76</sup> School of Physics and Astronomy, Queen Mary University of London, London, UK
- <sup>77</sup> Department of Physics, Royal Holloway University of London, Surrey, UK
- <sup>78</sup> Department of Physics and Astronomy, University College London, London, UK
- <sup>79</sup> Louisiana Tech University, Ruston LA, USA
- <sup>80</sup> Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- <sup>81</sup> Fysiska institutionen, Lunds universitet, Lund, Sweden



- 82 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- 83 Institut für Physik, Universität Mainz, Mainz, Germany
- 84 School of Physics and Astronomy, University of Manchester, Manchester, UK
- 85 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- 86 Department of Physics, University of Massachusetts, Amherst MA, USA
- 87 Department of Physics, McGill University, Montreal QC, Canada
- 88 School of Physics, University of Melbourne, Victoria, Australia
- 89 Department of Physics, The University of Michigan, Ann Arbor MI, USA
- 90 Department of Physics and Astronomy, Michigan State University, East Lansing MI, USA
- 91a INFN Sezione di Milano, Italy
- 91b Dipartimento di Fisica, Università di Milano, Milano, Italy
- 92 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- 93 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- 94 Group of Particle Physics, University of Montreal, Montreal QC, Canada
- 95 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- 96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 97 National Research Nuclear University MEPhI, Moscow, Russia
- 98 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- 99 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 101 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 102 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- 103a INFN Sezione di Napoli, Italy
- 103b Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- 104 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, USA
- 105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands
- 106 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, The Netherlands
- 107 Department of Physics, Northern Illinois University, DeKalb IL, USA
- 108 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- 109 Department of Physics, New York University, New York NY, USA
- 110 Ohio State University, Columbus OH, USA
- 111 Faculty of Science, Okayama University, Okayama, Japan
- 112 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, USA
- 113 Department of Physics, Oklahoma State University, Stillwater OK, USA
- 114 Palacký University, RCPTM, Olomouc, Czech Republic
- 115 Center for High Energy Physics, University of Oregon, Eugene OR, USA
- 116 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- 117 Graduate School of Science, Osaka University, Osaka, Japan
- 118 Department of Physics, University of Oslo, Oslo, Norway
- 119 Department of Physics, Oxford University, Oxford, UK
- 120a INFN Sezione di Pavia, Italy
- 120b Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- 121 Department of Physics, University of Pennsylvania, Philadelphia PA, USA
- 122 National Research Centre "Kurchatov Institute" B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- 123a INFN Sezione di Pisa, Italy
- 123b Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, USA
- 125a Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal
- 125b Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
- 125c Department of Physics, University of Coimbra, Coimbra, Portugal
- 125d Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
- 125e Departamento de Física, Universidade do Minho, Braga, Portugal
- 125f Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
- 125g Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- 126 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- 127 Czech Technical University in Prague, Praha, Czech Republic
- 128 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- 129 State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- 130 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK
- 131a INFN Sezione di Roma, Italy
- 131b Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- 132a INFN Sezione di Roma Tor Vergata, Italy
- 132b Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 133a INFN Sezione di Roma Tre, Italy
- 133b Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- 134a Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco
- 134b Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco
- 134c Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
- 134d Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
- 134e Faculté des sciences, Université Mohammed V, Rabat, Morocco
- 135 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- 136 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, USA

- 137 Department of Physics, University of Washington, Seattle WA, USA
- 138 Department of Physics and Astronomy, University of Sheffield, Sheffield, UK
- 139 Department of Physics, Shinshu University, Nagano, Japan
- 140 Fachbereich Physik, Universität Siegen, Siegen, Germany
- 141 Department of Physics, Simon Fraser University, Burnaby BC, Canada
- 142 SLAC National Accelerator Laboratory, Stanford CA, USA
- 143a Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovakia
- 143b Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- 144a Department of Physics, University of Cape Town, Cape Town, South Africa
- 144b Department of Physics, University of Johannesburg, Johannesburg, South Africa
- 144c School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- 145a Department of Physics, Stockholm University, Sweden
- 145b The Oskar Klein Centre, Stockholm, Sweden
- 146 Physics Department, Royal Institute of Technology, Stockholm, Sweden
- 147 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, USA
- 148 Department of Physics and Astronomy, University of Sussex, Brighton, UK
- 149 School of Physics, University of Sydney, Sydney, Australia
- 150 Institute of Physics, Academia Sinica, Taipei, Taiwan
- 151 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- 152 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- 153 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- 154 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- 155 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- 156 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- 157 Department of Physics, University of Toronto, Toronto ON, Canada
- 158a TRIUMF, Vancouver BC, Canada
- 158b Department of Physics and Astronomy, York University, Toronto ON, Canada
- 159 Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
- 160 Department of Physics and Astronomy, Tufts University, Medford MA, USA
- 161 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- 162 Department of Physics and Astronomy, University of California Irvine, Irvine CA, USA
- 163a INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
- 163b ICTP, Trieste, Italy
- 163c Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- 164 Department of Physics, University of Illinois, Urbana IL, USA
- 165 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- 166 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- 167 Department of Physics, University of British Columbia, Vancouver BC, Canada
- 168 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- 169 Department of Physics, University of Warwick, Coventry, UK
- 170 Waseda University, Tokyo, Japan
- 171 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- 172 Department of Physics, University of Wisconsin, Madison WI, USA
- 173 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- 174 Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- 175 Department of Physics, Yale University, New Haven CT, USA
- 176 Yerevan Physics Institute, Yerevan, Armenia
- 177 Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- 178 Also at Department of Physics, King's College London, London, UK
- 179 Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- 180 Also at Novosibirsk State University, Novosibirsk, Russia
- 181 Also at TRIUMF, Vancouver BC, Canada
- 182 Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA
- 183 Also at Department of Physics, California State University, Fresno CA, USA
- 184 Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
- 185 Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
- 186 Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal
- 187 Also at Tomsk State University, Tomsk, Russia
- 188 Also at Università di Napoli Parthenope, Napoli, Italy
- 189 Also at Institute of Particle Physics (IPP), Canada
- 190 Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK
- 191 Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 192 Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA
- 193 Also at Louisiana Tech University, Ruston LA, USA
- 194 Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
- 195 Also at Graduate School of Science, Osaka University, Osaka, Japan
- 196 Also at Department of Physics, National Tsing Hua University, Taiwan
- 197 Also at Department of Physics, The University of Texas at Austin, Austin TX, USA
- 198 Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
- 199 Also at CERN, Geneva, Switzerland
- 200 Also at Georgian Technical University (GTU), Tbilisi, Georgia

- <sup>201</sup> Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan  
<sup>202</sup> Also at Manhattan College, New York NY, USA  
<sup>203</sup> Also at Hellenic Open University, Patras, Greece  
<sup>204</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan  
<sup>205</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan  
<sup>206</sup> Also at School of Physics, Shandong University, Shandong, China  
<sup>207</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia  
<sup>208</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland  
<sup>209</sup> Also at International School for Advanced Studies (SISSA), Trieste, Italy  
<sup>210</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA  
<sup>211</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China  
<sup>212</sup> Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia  
<sup>213</sup> Also at National Research Nuclear University MEPhI, Moscow, Russia  
<sup>214</sup> Also at Department of Physics, Stanford University, Stanford CA, USA  
<sup>215</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary  
<sup>216</sup> Also at Flensburg University of Applied Sciences, Flensburg, Germany  
<sup>217</sup> Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia  
<sup>218</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France  
<sup>219</sup> Deceased